External Noise Issues in VLHC

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1 Introduction

There are several proposals of the "beyond-LHC" large colliders with 30–100 TeV beam energy and luminosity of $10^{33} - 10^{35}\ s^{-1}cm^{-2}$. During 1997 Summer Studies we focused on beam dynamics issues in the Very Large Hadron Collider (VLHC). Many sources of noises which are of interest for the VLHC operation are considered in Ref.[1] and there is shown that the effects of transverse and longitudinal emittance growths due to RF noise and longitudinal emittance increase due to ground motion most probably will be negligible, and they are out of consideration in this paper. The issues of real importance are transverse emittance growth due to dipole field ripple and quadrupole jitter, emittance preservation with a feedback system for damping of the coherent oscillations, orbit oscillations, long-term dynamical alignment and orbit correction scenario.

This paper contains explanations and estimates of the effects. Tolerances are calculated three machines: 50 TeV collider with 12.5T magnetic field dipoles [2], low-field option of superferric 2T magnet machine with larger circumference, 50 TeV "Pipetron" [3], and 3 TeV injector ring with low-field magnets. Some of input parameters can be found in the "pink book" of Snowmass'96 reports [4], others were taken from the VLHC Summer Studies contributions by E.Malamud and S.Mishra. The rest of the paper contains brief explanation of the numbers presented in Table 1.

The accelerators under consideration are large, they consist of thousands of magnetic elements, the field imperfections of those can seriously affect proper machine operation. Depending on the frequency band one can distinguish two mechanisms of beam perturbations in circular accelerator. Slow processes (with respect to revolution period) produce a distortion of the closed orbit of the beam. At higher frequencies (comparable with the revolution frequency), noises cause direct emittance growth.

Table 1: External Noise Tolerances in VLHC

Parameter		Low-Field	High-field	Injector	Comments
Proton Energy,	E_p, TeV	50	50	50	50
Dipole field,	B, T	2.0	12.5	2.0	
Circumference,	C, km	551.2	104.0	34.0	
Rev.frequency	f_0, Hz	544	2885	8824	$f_0 = c/C$
Tune (phase/cell),	ν (μ)	215.82 (90)	52.82 (90)	33.18 (90)	
f_1=$\Delta\nu f_0$,	Hz	98	520	1588	
Number of cells,	N_c	1100	208	198	
Number of quads,	N_q	2200	416	396	
Number of dipoles,	N_d	2200	416	348	
Beam-beam tune shift,	ξ_p	0.006	0.001	-	
RMS emittance,	$\epsilon_n,\ 10^{-6}\,m$	1	1	1	
Beam-time,	τ, hrs	5	2.6	0.1	
Emm. growth rate,	$d\epsilon_n/dt$, μm/hr	0.02	0.04	1	$0.1\epsilon_n/\tau$
Dipole fluct.,	$\delta B/B$, 10^{-10}	2.3	0.7	10.3	
Quad jitter,	δX, A	1.05	1.5	115	1 A=0.1 nm
δX comb.function,	δX_{cf}, A	3.0	4.3	200	$L_{coh} = 30$ m
PSD of quad vibr.,	$S_x(f_1)$, pm^2/Hz	20	8	15000	
Expected PSD,	$\frac{pm^2}{Hz}$	180	0.2	0.003	$\delta X = \frac{0.3[\mu m]}{f^{3/2}}$
Max. PSD,	pm^2/Hz	25000	1000	4	$\delta X = \frac{0.1[\mu m]}{f}$
Max FB reduction,	R	240	32000	-	
FB input noise,	δX_{FB}, μm	0.8	5	-	
FB power,	P_{FB}, kW	5	5	-	$\Delta f = 1$ MHz
Orbit oscillations,	δ/σ	0.14	0.06	0.025	
Init. alignment,	Δ_{rms}, μm	10	20	50	quad-to-quad
RMS orbit,	COD, mm	$0.2\sqrt{T}$	$0.09\sqrt{T}$	$0.05\sqrt{T}$	$T[hrs]$
Max orbit,	COD_{max}, mm	$1\sqrt{T}$	$0.45\sqrt{T}$	$0.25\sqrt{T}$	max=5 r.m.s.
Realign intervals,	T, days	4	21	67	
Max. corrector,	$T \cdot m$	0.67	0.67	0.07	T=1 yr no

2 Transverse Emittance Growth

2.1 Effect of Transverse Kicks

The primary sources which lead to emittance growth in large hadron colliders are quadrupoles (quad) jitter and high-frequency variations of the bending magnetic field in dipoles. Both sources produce angular kicks and excite coherent betatron oscillations. After decoherence time (determined mostly by beam-beam non-linearities,

$N_{decoh} = 1200$ turns) filamentation or dilution process due to tune spread within the beam transforms the coherent oscillations into the emittance increase. If the kick amplitude $\Delta\theta$ varies randomly from turn to turn with variance of $\delta\theta^2$, one can estimate the transverse emittance growth as:

$$\frac{d\epsilon_n}{dt} = \frac{1}{2} f_0 \gamma \sum_i^{all\,kicks} \Delta\theta_i^2 \beta_i = \frac{1}{2} f_0 \gamma \delta\theta^2 < \beta > N \tag{1}$$

where $< \beta >$ is the average beta function, γ is relativistic factor, and N is the number of elements which produce uncorrelated kicks. Two major sources of the dipole kicks are fluctuations δB of the bending dipole magnetic field B_0 which give horizontal kick of $\delta\theta = \theta_0(\delta B/B_0)$ ($\theta_0 = 2\pi/N_d$ is bending angle in each dipole, N_d is total number of dipoles); and transverse quadrupole magnets displacements δX (e.g. due to ground motion) which lead to kick of $\delta\theta = \delta X/F$, where F is the quadrupole focusing length.

Non-"white" noise can be described by frequency-dependent power spectral density(PSD) $S_{\delta\theta}(f)$, and causes the emittance growth with rate of [5]:

$$\frac{d\epsilon_n}{dt} = \gamma f_0^2 \sum_i \Big(\beta_i \sum_{n=-\infty}^{\infty} S_{\delta\theta}(f_0|\nu - n|) \Big), \tag{2}$$

which consists of the sum of PSDs of angular kicks produced by the i-th source at frequencies of $f_0|\nu - n|$, n is integer, the lowest of them is fractional part of the tune times revolution frequency f_1 =Min $(\Delta\nu, (1 - \Delta\nu))f_0$.

Beam lifetime in the Pipetron is about $\tau = 5$ hours (determined mostly by longitudinal intrabeam scattering [1] $\tau_{\|}^{IBS} \approx 6$ hrs, while synchrotron radiation transverse damping time is about 42 hours). The characteristic time interval of 2.6 hours in the high-field VLHC option is set by the synchrotron radiation. For 3TeV low-field injector we take the beam life-time of 6 min - it is about duration of the acceleration from the Main Injector energy of 150 GeV to 3 TeV.

We require that the external noise lead to less than 10% emittance increase while the beam circulates in the accelerator. Then we get tolerable the noise-induced emittance growth rate of

$$\frac{d\epsilon_n}{dt} \leq 0.1 \frac{\epsilon_n}{\tau} \tag{3}$$

(see data in Table 1).

This acceptable transverse emittance growth rate requires for the "Pipetron":
a) the PSD of single quadrupole transverse vibration is limited by the value of $\sum_n S_{\delta X}(f_0|\nu - n|) \approx S_{\delta X}(f_0 \Delta\nu) \leq 2 \cdot 10^{-11} \frac{\mu m^2}{Hz} = 20 \frac{pm^2}{Hz}$, where $\Delta\nu$ is fractional part of ν;
b) or the rms amplitude of turn-to-turn jitter of each quadrupole (white noise in frequency band f_0) $\delta X_{rms} \leq 1 \cdot 10^{-10}$m; [1]

[1] quadrupole turn-to-turn jitter tolerance in the combined function lattice is about 3 times larger. Indeed, if we consider $L = 250$m long quadrupole as 9 quadrupoles each about $L_{coher} = 30$m long

c) and a tolerable level of bending magnetic field fluctuations to its mean value B_0 in the dipole: $\left(\delta B/B_0\right)_{rms} \leq 2.3 \cdot 10^{-10}$. [2] See the numbers for other machines in Table 1.

2.2 Measured Ground Motion

Let us make a comparison of the above calculated constraints with experimental data on ground motion. Fig.1 presents PSDs of ground velocity $S_x(f)(2\pi f)^2$ in units of $(\mu m/s)^2/Hz$ for the USGS "New Low Noise Model" – a minimum of the PSD observed by geophysicists worldwide – and data from accelerator facilities of HERA, KEK, CERN, SLAC, and FNAL (see references in [1]). These spectra indicate that: 1) accelerators are essentially "noisy" places; 2) ground vibrations above 1 Hz are strongly determined by cultural noises – they manifest themselves as numerous peaks in Fig.1; 3) even among accelerator sites the difference is very large, that calls for extensive experimental studies of the seismic vibrations at FNAL.

Below 1 Hz the ground motion amplitude is about 0.3-1 μm due to remarkable phenomena of "7-second hum". This hum is waves produced by oceans – see a broad peak around 0.14 Hz in Fig.1 – with wavelength of about $\lambda \simeq 30$ km. It produces negligible effect on Pipetron, because λ is much bigger than typical betatron wavelength $2\pi\beta \simeq 2$ km. Investigations of spatial characteristics of the fast ground motion have shown that above 1-4 Hz the correlation significantly drops at dozens of meters of distance between points.

Table 2 compares requirements for the Pipetron with three particular tunes $\Delta\nu = 0.10,\ 0.18$ and 0.24 and available experimental data.

Table 2: PSD of Ground Motion (in $(pm)^2/Hz$)

$\Delta\nu$	0.10	0.18	0.24
$f_1 = \Delta\nu f_0$	54 Hz	98 Hz	135 Hz
Pipetron tolerance	**20**	**20**	**20**
SLAC (quiet)	100	-	-
DESY (tunnel)	10^5	7000	1700
CERN (tunnel)	300	20	-

One can see that none of the accelerator data shows vibrations which are less than the Pipetron requirements, although PSDs at higher frequencies (say $f_1 = 135$ Hz) are much less than at lower frequency of 54 Hz, and, therefore, larger $\Delta\nu$ – closer to half integer resonance – are preferable from this point of view. At $\Delta\nu = 0.18$ one needs the vibration power reduction factor of $R \simeq 10 - 1000$ (see Table 1). For other machine estimates we assumed that there is a "rule of thumb" which says that rms amplitude of the vibrations X above some frequency f is equal

(i.e. each nine times weaker) which move independently, then we get that for the same amplitude of the vibrations, the increase of the emittance will be 9 times less.

[2] one again, we emphasize that this tolerance assumes variation of the total integrated field of 250m long dipole.

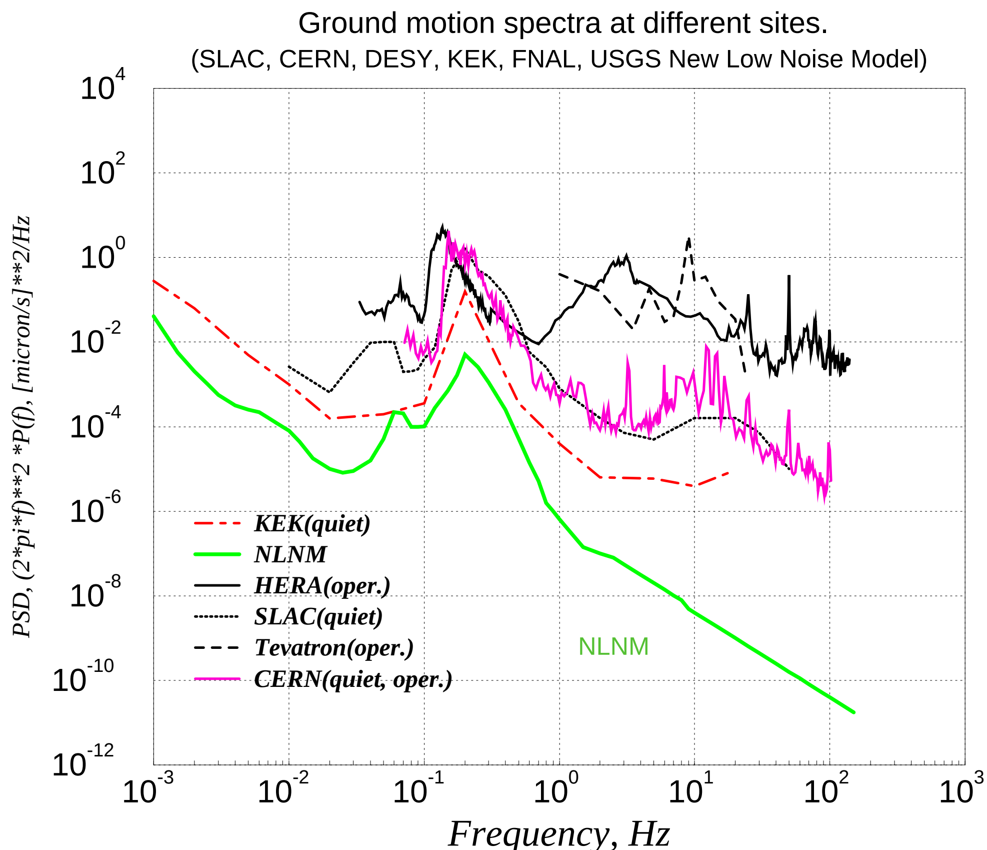

Figure 1: Measured ground velocity spectra.

to $r.m.s.X = B/f[Hz]$ (here B is a constant) which corresponds to the PSD of $S_x(f) = 2B^2/f^3$. Within a factor of 4 this rule usually fits well the accelerators-averaged vibration amplitudes above 1 Hz under "quiet" conditions. Fig.2 presents the values of $rmsX(f) = \int_f^\infty S_x(f)df$ calculated for several spectra from Fig.1 – namely, for SLAC, CERN, HERA, and FNAL data. The measurement of tunnel floor vibration amplitude made in the Tevatron tunnel at FNAL covers frequencies of 1–25 Hz and can be approximated by the "rule of thumb" with $B = 100$ nm. Although there is no data on FNAL site vibrations at high frequencies, we will use the fit predictions above 25 Hz as well. From Fig.2 one can see that the same coefficient B is applicable for the HERA tunnel amplitudes, while ground motion in tunnels of SLC(SLAC) and TT2A(CERN) are about 10-20 times smaller. This "rule of thumb" was used for maximum estimates of the PSD of ground vibrations at high frequencies. As the "quiet" PSD we took $r.m.s.X = 0.3[\mu m]/f^{3/2}[Hz]$. Both expectations are quoted in Table 1.

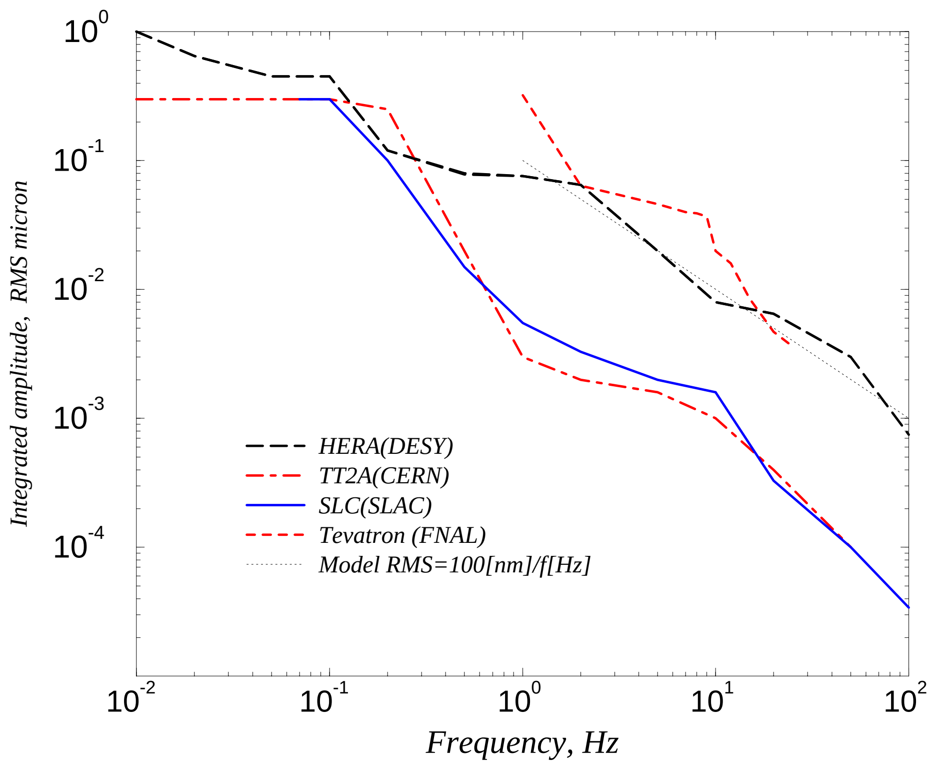

Figure 2: RMS amplitude above f vs. f.

We have no experimental data on dipole field fluctuations at 50-150 Hz and mechanical resonances in long dipoles and quadrupoles which may drastically increase the emittance growth.

2.3 Feedback System

A transverse feedback frequency allows one to suppress the emittance growth caused by excitation of the betatron oscillations simply by damping the coherent beam motion faster then they decohere. The system monitors the dipole offset X of the beam centroid and tries to correct it by dipole kicks θ which are proportional to the offset, applied a quarter of the betatron oscillation downstream. We operate with dimensionless amplification factor g of the system (gain) which is equal to $g = \frac{\theta\sqrt{\beta_1\beta_2}}{X}$, where β_1 and β_2 are the beta-functions at the positions of the pick up and the kicker electrodes respectively. In the limit of $g \ll 1$ the decrement due to the feedback is equal to $\frac{1}{2}f_0 g$, i.e. the amplitude of the betatron oscillations being reduced $1/e$ times after $2/g$ revolution periods. Theory of the feedback (see e.g. [5]) gives the transverse emittance evolution formula:

$$\frac{d\epsilon_n}{dt} = \Big(\frac{4\pi\delta\nu_{rms}}{g}\Big)^2 \Big[\Big(\frac{d\epsilon_n}{dt}\Big)_0 + \frac{\gamma f_0 g^2}{2\beta_1} X^2_{noise}\Big], \tag{4}$$

$g \gg 4\pi\delta\nu_{rms}$, where emittance growth rate without feedback $(d\epsilon_n/dt)_0$ is given by (1), X_{noise} is the rms noise of the system (presented as equivalent input noise at the pick-up position), and $\delta\nu_{rms}$ is the rms tune spread within a beam.

Major source of the tune spread (and, consequently, decoherence) is nonlinear beam-beam force which results in the rms tune spread of $\delta\nu_{BB} \approx 0.167\xi \approx 0.001.$

Analytical consideration of the feedback system resulted in maximum useful gain factor $g_{max} \simeq 0.3$ – there is no reduction of the emittance growth rate with further increase of g because of higher-(than dipole)-order kicks effect, the system noise contribution grows, while the coherent tune shift due to feedback becomes too large, and affects multibunch beam stability in presence of resistive wall impedance.

Therefore, maximum reduction factor $R_{max} = (g_{max}/4\pi\Delta\nu_{BB})^2$ is about 240 for the Pipetron design parameter of $\xi = 0.006$, while the minimum practical gain which still can lead to the damping is about $4\pi\delta\nu_{BB} \approx 0.01$. For the high-field option of the VLHC with smaller ξ, the maximum reduction factor R can reach $3{\cdot}10^4$.

As it is seen from (2.3), feedback noise also leads to emittance growth and its relative contribution grows as $\propto g^2$. Taking the beta function at the pick-up $\beta_1 = 500$m we get limit on the rms noise amplitude:

$$X_{noise} \ll \Big[\frac{2\beta_1(d\epsilon_n/dt)_0}{f_0(4\pi\delta\nu_{BB})^2\gamma}\Big]^{1/2} \approx 1.0\,\mu m. \tag{5}$$

Power of the output amplifier of the system depends on maximum noise amplitude of the proton beam oscillations and is estimated to be about 50 kW for a bunch-by-bunch system[1].

3 Closed Orbit Distortions

3.1 Alignment Tolerances

The rms closed orbit distortion dX_{COD} is proportional to the rms error dX of quads alignment, and if these errors are not correlated, then in the FODO lattice we can get:

$$dX^2_{COD} = \frac{\beta dX^2}{4sin^2(\pi\nu)} \sum_i \frac{\beta_i}{F_i^2} = \frac{\beta N_q tg(\mu/2) dX^2}{L sin^2(\pi\nu)}. \tag{6}$$

Let us take the "safety criteria", i.e. ratio of maximum allowable COD to the rms one, equal to 5, then for maximum COD of dX^{max}_{COD}=1 cm (this is about half aperture of the vacuum chamber) at the focusing lenses where $\beta_F = 765$ m ($L = 250$ m, $\mu = 90^o$) we get requirement on the rms alignment error of $dX \approx 10\,\mu$m (here we take $\Delta\nu = 0.18$). The same estimate for the quad-to-quad alignment in the high-field VLHC gives 20μm and 50μm for the 3TeV injector (see Table 1). These values set a challenging task, and the solution needs the most sophisticated alignment techniques and two questions arise in this connection: 1) temporal stability of the magnets positions; and 2) applicability of the beam-based alignment.

3.2 Slow Ground Motion

Numerous data on uncorrelated slow ground motion support an idea of "space-time ground diffusion". An empirical rule that describes the diffusion – so called "the ATL law" [8] – states the rms of relative displacement dX (in any direction) of two points located at a distance L grows with time interval $T < dX^2 >= ATL$, where A is site dependent coefficient of the order of $10^{-5\pm1}\ \mu m^2/(s \cdot m)$.

The ground diffusion should cause corresponding closed orbit diffusion (COD) in accelerators [3] with rms value over the ring approximately equal to $\langle dX^2_{COD} \rangle \simeq 2\sqrt{ATC}$. It clearly shows that the diffusive orbit drift is not very sensitive to the focusing lattice type (only the circumference C plays role), in particular, there is almost no difference between the combined- and separated-function lattices responses on the ATL-like diffusion.

We applied the ATL law predictions with $A \approx 5 \cdot 10^{-5}\ \mu m^2/(s \cdot m)$ (close to what was observed at LEP) to the VLHC (see [1]) and obtained the rms COD – see Table 1. Maximum COD is taken to be five times the rms COD, e.g. for the low-field option $dX^{max}_{COD} \approx 1[mm]\sqrt{T[hrs]}$. Requirement of "safe" max COD of 10 mm yields in T=4 days of mean time between necessary realignments to an initial "smooth" orbit of the low-field VLHC. It does not seem to be an easy task to do it mechanically, even with use of robots, especially taking into account 15 μm precision of the procedure. "Beam-based alignment" technique looks as an appropriate method but requires numerous (of the order of the number of quads) correctors with about 1 Tm maximum strength.

4 Conclusion. R&D plans.

Preceding consideration shows that natural and man-made vibrations at the VLHC can lead to dangerous transverse emittance growth rate (high-frequency part of spectrum) and closed orbit distortions (at low frequencies). Being comparable, the tolerances on quadrupole turn-to-turn vibrations are somewhat less stringent at the high-field option. For the dipole field fluctuations the relation is opposite. 3TeV injector seems free of troubles with the transverse emittance growth. Longitudinal emittance in all the machines is almost independent on the external noises [1]. The transverse feedback system can drastically reduce the transverse emittance increase.

Wandering of the parts of the tunnel can be a major problem for the orbit stability in all the considered accelerators (the conclusion is based on the other places' data). Sophisticated alignment methods are necessary to keep the VLHC and 3TeV

[3] observed in HERA [9]

injector beams on a “golden orbit”.

The VLHC R&D on the external noise issues.

- In Aug.-Oct. 1997 we are going to carry out “on-site” ground motion studies and magnet vibrations measurements in frequency band 0.05-150 Hz. It will answer the question of the ground motion contribution to the transverse emittance growth.
- Other important contribution can be the dipole field jitter. It definitely must be measured.
- There is real need in experimental data on long-term tunnel movements which will determine the long-term orbit stability and the correction scenario. Experiments with 30-300 m long hydrostatic levels in a similar to the VLHC tunnel can shed the light on the issue.

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